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ERROR ANALYSIS AND PERFORMANCE DATA FROM AN AUTOMATED AZIMUTH MEASURING SYSTEM

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ABSTRACT

The determination of precise time-dependent azimuths is an important requirement for evaluation and maintenance of inertial navigation instruments. Improved technology now demands a test and evluation accuracy of less than one arc second, which means that geophysical and environmental effects on the time-stability of azimuth references are now quite significant. Similarly, azimuthal motions of the test equipment, which are inherent in the tests themselves, must also be evaluated. This paper discusses an automated inertial azimuth measuring system which was used to track the azimuthal motion of test references at Holloman AFB, NM. A detailed error analysis of the system and methods to improve performance and accuracy are presented. Discussion includes selected alternatives for improving state-of-the art azimuth measurement.

I. Introduction

To accurately and continuously determine rotational motions about a vertical axis the Air Force Geophysics Laboratory (AFGL) developed an Automated Azimuth Measuring System (AAMS). The AAMS has been used to measure the azimuthal motion environment at missile test silos[1] and an inertial guidance component test facility. Major components of the AAMS are shown in Figure 1. It consists of two gyrocompass devices, termed Azimuth Laying

Figure 1. AFGL Automated Azimuth Measuring System

Sets (ALS's), an inductosyn/autocollimator azimuth transfer system, microprocessors, tape drives, input and output hardware, a dual-axis tiltmeter mounted on the azimuth gimbal of each ALS, and six tiltmeters arranged on an optical table. This equipment is enclosed in a plexiglass environmental shield with low velocity air flowing through tubes along the optical paths to each target. Temperature sensors are located in each ALS, the enclosure and the ambient environment. A detailed description of the AAMS is contained in reference 2.

In September of 1979, the AAMS was used by AFGL at the Advanced Inertial Test Laboratory (AITL), Holloman AFB, NM, to characterize the motions of several azimuth references. A Porro prism, an optical cube on the gyro test table and an astronomic azimuth transfer cube were continuously monitored for several days. The azimuth measurement scheme is shown in Figure 2.

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Holloman AFB, NM. A detailed error analysis of the system and methods to improve performance and accuracy are presented. Discussion includes selected alternatives for improving state-of-the-art azimuth measurement.

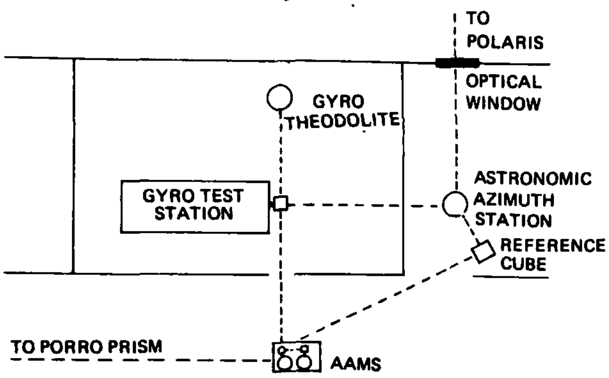

Figure 2. Azimuth Measurement Scheme Advanced Inertial Test Laboratory

Astronomic azimuths were also observed concurrent with and subsequent to the AAMS measurements in the AITL through a newly constructed window that permitted direct observation of Polaris from within the building. These observations were directly transferred to the gyro test table cube and the reference cube from the observation station. Astronomic azimuths were also observed outside the facility by the DMAAC/Geodetic Survey Squadron and transferred to the Porro prism during 1976-1979. These data are given in reference[3].

Processing of the AITL data has not been completed but should be available for dissemination at the AIAA Guidance and Control Conference, August 1980. Following this study, an error analysis of the AAMS was performed by the Charles Stark Draper Laboratory (CSDL). This paper presents the results of this accuracy assessment of the AAMS completed to date, and design and performance goals for a CSDL Single-Degree-of-Freedom gyro to be used in a Wheel-Speed Modulation (WSM) mechanization for more accurate and rapid measurements of azimuth.

II. Accuracy Assessment of the AAMS

The Charles Stark Draper Laboratory (CSDL) is presently evaluating the accuracy limitations of the AAMS. Although this evaluation includes all major components, only the ALS will be discussed in this paper.

Description of the Azimuth Laying Set

An Azimuth Laying Set uses one single-degree-of-freedom floated GI-T1-B gyro to directly measure the earth rate component along its input axis. Figure 3 is a functional representation of the gyro as it is configured in the ALS.

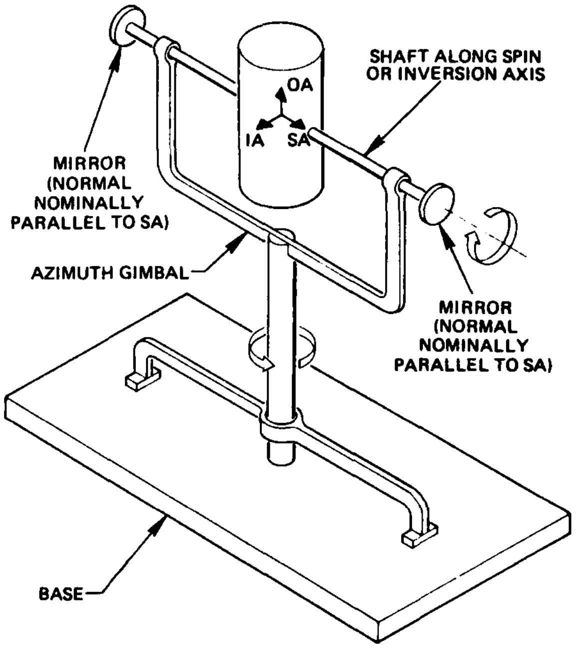

Figure 3. Functional Representation of ALS

The gyro is mounted on an inner gimbal with its spin axis parallel to the gimbal rotation axis, which is nominally horizontal and parallel to the north south line. (This gimbal axis is named the inversion axis because a 180° rotation about it changes the gyro orientation from gyro output axis up to gyro output axis down.) The inner gimbal is in turn mounted on an azimuth gimbal whose axis is nominally aligned parallel to the vertical.

A flat mirror is mounted on each end of the inner gimbal inversion axis with the mirror face normal nominally parallel to the inversion axis. The mirrors therefore rotate with the gyro about the inversion axis and are slewed 180° with the gyro as it gyrocompasses from IA east to west.

Optical transfer from the ALS to any external point is made through measurement of the horizontal angle between the ALS mirror normal and the target normal. The inversion axis is defined as the ALS reference axis, and its deviation from north is measured by the gyro as shown in Figure 4.

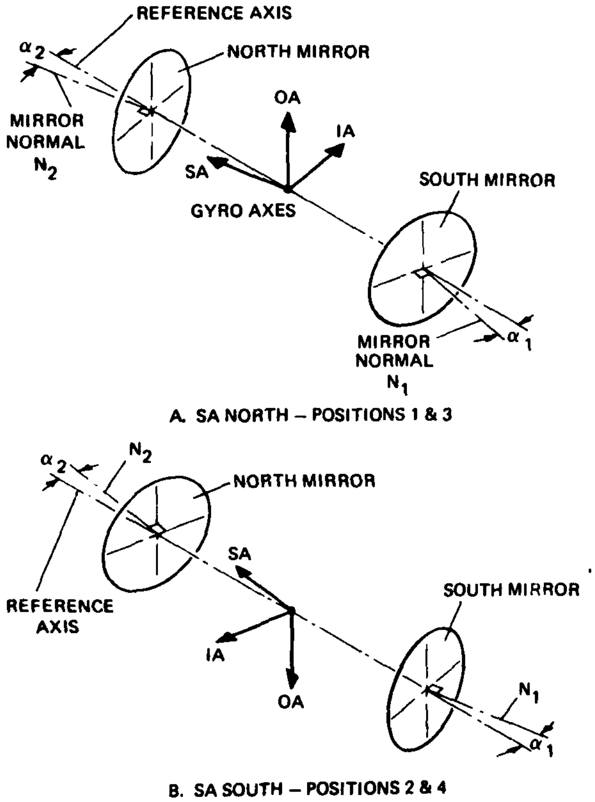

Figure 4. Misalignment Angles During ALS Gyrocompassing Sequence

Tiltmeters are mounted on the azimuth gimbal in order to sense earth rate due to tilt about the gyro spin axis, and direct tilt rate about the gyro input axis. Corrections are then made to the gyro output data using the tiltmeter data.

In its normal operational mode, the ALS is gyrocompassed by rotating the gyro about each of its two gimbal axes. Average gyro rate is obtained from a 100 second sample interval for each of the four nominal orientations listed below in Figure 5. An azimuth axis servo and inversion axis servo are used to automatically position the gimbals.

	Gyro Axes			
ALS Position	Output (OA)	Spin (SA)	Input (IA)	Mirror Used
1	Up	North	East	#1
2	Down	North	West	#1
3	Up	South	West	#2
4	Down	South	East	#2

Figure 5. ALS Gyrocompassing Sequence

The deviation of the inversion axis (or optical reference axis) from north is given by

$$\phi_A = \frac{\omega_1 - \omega_2 + \omega_3 - \omega_4 - \omega_I - \omega_S}{4\omega_h} \qquad (1)$$

where

ω_i = gyro output in orientation i

ω_h = horizontal component of earth rate

ω_v = vertical component of earth rate

ω_I = cumulative tilt rate about IA

ω_S = cumulative tilt rate about SA due to ω_v

and

ϕ_A is a small angle.

Theoretical Error Sources

It can be shown that the use of the four orientation gyrocompassing sequence with the tiltmeters and the assumptions of rigid ALS gimbals and no appreciable gyro float motion lead to cancellation or compensation for the following potential sources of error from any single orientation:

(a) Misalignment of the gyro axes with respect to the inversion and azimuth axes.

(b) Misalignment of the mirror normals with respect to the inversion axis.

(c) Non-180° rotation about the vertical (azimuth) axis.

(d) Gyro bias and output axis mass unbalance.

(e) Tilt and tilt rate as described above.

(f) Gyro torque to balance loop scale factor error.

Potentially significant error sources which do not cancel are now coming under serious consideration due to present sub-arc second performance goals. Some of these sources are as follows:

(a) Inversion axis servo non-repeatability which leads to a direct error in the estimation of deviation of the reference axis from north given by

$$E_\theta = \frac{\tan L}{4} (\delta\theta_2 + 2\delta\theta_3 + \delta\theta_4)_h \qquad (2)$$

where

L = latitude

$(\delta\theta_i)_h$ = inversion axis servo null error for the i^{th} orientation as measured in the horizontal plane.

Also, the gyro input axis mass unbalance term will no longer cancel since it varies with servo nonrepeatability, as given by the equation

$$E_{M_I} = \frac{gM_I}{4\omega_h} (\delta\theta_2 + 2\delta\theta_3 + \delta\theta_4)_h \qquad (3)$$

where M_I = gyro input axis mass unbalance coefficients.

(b) Inversion axis and azimuth axis servo dither lead to real time variations in both the rate sensed by the gyro and the angular position defined by the optical axis which can only be dealt with by proper data processing.

(c) Deflection of the inversion axis gimbal results in a lack of unique definition of the inversion axis when using the two ALS mirrors. This error could be either fixed or time varying depending upon the cause of the gimbal flexure.

(d) Gyro float motion with respect to the gyro case from one ALS orientation to the next results in time varying gyro misalignment angles due to multiple gyro orientations and tilt variations between orientations. These errors do not necessarily cancel over the four orientation sequence and can lead to a direct error in gyrocompassing.

(e) Gyro random errors also lead to a direct error in gyrocompassing. Of particular importance is the magnitude and shape of the gyro drift power spectral density and its relation to the data processing that is used. The gyro output during each orientation is averaged over a fixed time interval T. Thus, if the gyro power spectral density (PSD) contains significant power at frequencies above $\frac{1}{2T}$ aliasing can be a serious error source. [Aliasing results in rectification of the high frequency portion of the spectrum as an error in the average gyro output.]

(f) Additonal errors due to float motion are contributed by the gyro input axis mass unbalance, the spin axis mass unbalance and two gyro anisoelastic error terms. Gimbal wobble also results in contributions from the spin axis mass unbalance and the gyro anisoelastic terms.

Laboratory Evaluation of the AAMS

The AAMS including the two ALS units is currently being evaluated at CSDL. Attention is focused on the potential significant error sources listed above. Thus far results have been obtained for inversion axis servo repeatability, azimuth and inversion axis servo dither, and deflection of the inversion axis shaft.

An optical cube was mounted on one end of the inversion axis in place of the flat mirror in order to be able to monitor rotations of the inversion axis with an autocollimator. The autocollimator was initially nulled, and subsequent deviations measured with successive rotations of the inversion axis shaft were referenced to the initial null. Two estimates of servo repeatability were made. An optimistic measure assumed that the true servo null was the average of the deviations from the initial null, and therefore used the standard deviation of the mean to describe servo repeatability. A conservative measure took the largest difference between deviations from the initial autocollimator null.

ALS unit #1 had a standard deviation of 0.25 arc sec and a maximum deviation of 1 arc sec. ALS unit #2 had a standard deviation of 0.97 arc sec and a maximum deviation of 3 arc sec. At a latitude of 45°, the RSS deviations from Equation (2) are 0.15 arc sec and 0.52 sec, respectively for ALS #1 and ALS #2 for the uncertainty in aximuth due to inversion axis servo nonrepeatability. Worst case deviations are 1 arc sec and 3 arc sec, respectively.

Azimuth and inversion axis servo dither was also monitored by use of autocollimators. The power spectral densities for the dither are approximately flat between 0.003 Hz and 0.6 Hz. and then roll off at -60 db/decade above 0.6 Hz (At present it is not known how much of the rolloff is due to the autocollimator frequency response). Cumulative standard deviations computed from the PSD plots are approximately 0.31 arc sec and 0.17 arc sec for the inversion axis and azimuth axis, respectively for ALS #2 and about 0.13 arc sec for both axes for ALS #1. Because of the flat shape (i.e., "white noise" appearance) in the low frequency range and the rapid roll off above 0.6 Hz, this source of error will not significantly contribute to the final azimuth error after the normal data processing if most of the low frequency roll-off is due to the servo frequency response.

Preliminary results obtained for ALS #1 show that there may be an inversion gimbal axis deflection (i.e., "bent gimbal") of as much as 1 to 2 arc sec with warmup of the ALS from room temperature. Of obvious special interest is whether this deflection is repeatable when the ALS units are repeatedly cycled again from ambient to operating temperature.

Continued optical testing, measurements of gyro float motion during the ALS operating sequence, and determination of random gyro errors are planned for the remainder of the summer. In addition, improvements in gyro technology, tilt measurement and compensation, optical transfer of azimuth, automation and data processing are planned for the next several years. Several of these areas are discussed in the following sections.

III. Future Plans for Improving Instrumentation and Techniques

Traditionally, optical references have been used as azimuth holding devices, with an implied assumption that only long-term azimuth variations with periods of days or longer are significant. However, as accuracy demands increase, higher frequency, low amplitude motions of these references become of increasing concern. Portable inertial gyros such as the ALS, which employ the technique of gyrocompassing to minimize systematic errors, are presently considered to be the most accurate means of tracking the azimuthal motions of these references. Yet, the level of accuracy needed for the DoD systems is fast surpassing even the capabilities of these inertial instruments. Thus, the ALS instrument performance errors previously described, coupled with aging degradation of the GI-

T1-B gyros in the ALS units, are major factors to be considered in improving the accuracy of the entire AAMS.

Improved Gyro Technology

CSDL has addressed these limitations via improved single-degree-of-freedom (SDOF) gyro technology which eliminates the need for continuous multi-position gyrocompassing by Wheel-Speed Modulation (WSM). WSM is a gyroscope mode of operation in which wheel excitation frequency is varied in order to vary wheel angular momentum, or H. Performance improvements, such as stable and repeatable wheel power and reduced sensitivity of power with excitation frequency, now enable use of WSM as a more rapid and accurate approach to measuring azimuth. Since azimuth can be determined by WSM in a single gyro position, the mechanical and electrical uncertainties inherent in four-position gyrocompassing are eliminated as a major error source.

WSM for Azimuth Measurement[4]

Utilizing a SDOF gyro operating in a typical torque rebalance mode, and the gyro case fixed in space, the rebalance torque equals the precession torque plus error torques as described in Equation (4).

$$M_R = H\omega_{IA} + D_F + \Sigma\vec{a}_i(D_{UNB})_i + \Sigma\vec{a}_i^{\,2}(D_{COMP})_i + \Sigma\vec{a}_j(D_{UNB})_i + \Sigma\vec{a}_j^{\,2}(D_{COMP})_i \qquad (4)$$

where

$\vec{a}$ = acceleration vector along each gyro axis

M_R = rebalance torque

ω_{IA} = angular rate about the input axis

H = angular momentum of wheel

D_F = float bias torque

D_{UNB} = float unbalance torque along each gyro axis

D_{COMP} = compliance torque along each gyro axis

In order to measure azimuth to a system goal below one arc second, a rate measurement accuracy for ω_{IA} near 0.001 meru is required. (A change in ω_{IA} of 0.001 meru is sensed for an azimuth change of approximately 0.25 arc seconds at mid-US latitudes.) Thus for typical values of error coefficients which range from 10 to 100 meru, 100 to 10 ppm calibration accuracy is needed, with time stabilities to the same accuracies. Calibration to these accuracies utilizing conventional tumble testing presents a difficult challenge.

In contrast, relating torque changes to rate inputs through WSM does not require precise calibration nor stability of the standard error coefficients. However, it does require knowledge of the coefficient sensitivity to wheel-speed changes as seen from Equation (5). During wheel-speed modulation, H is varied and the associated change in rebalance torque becomes

$$\frac{\Delta M_R}{\Delta H} = \omega_{IA} + \frac{\Delta D_G}{\Delta H} \qquad (5)$$

where

D_G = combined first order gyro error torques

$$= D_F + \vec{a}_i(D_{UNB})_i + \vec{a}_i^{\,2}(D_{COMP})_i$$

Note that second order error torques can now be neglected since they are very small for ΔD_G.

For the special case of measuring azimuth, ω_{IA} will equal $\alpha\omega_{erh}$, where α is the azimuth angle and ω_{erh} is the horizontal component of earth rate. Assuming the angle of the spin axis (H vector) does not vary within the range of speed change and is orthogonal to the output axis (OA), the error degrading accuracy is $\Delta D_G/\Delta H$. Thus, if the speed-change-sensitive coefficients contained in the ΔD_G term are small (as with new gyro designs), large uncertainties can be tolerated, continued calibration is not required, and rate measurement accuracy is not lost.

As indicated, the ability to continuously measure azimuth with WSM is contingent upon both the magnitude and stability of $\Delta D_G/\Delta H$. Obviously, since gyro rebalance torque is sensitive to speed changes, this torque sensitivity will limit measurement accuracy if not compensated. But this sensitivity can be readily calibrated and if a correction is applied, only the stability would then corrupt accuracy.

Torque stability, in turn, is a function of power dissipation and repeatability with each change in wheel speed. CSDL test data indicate that these factors are not limitations within the desired gyro performance goal below one arc second.

Finally, one must consider optimizing the gyro wheel speed change by comparing signal to noise resolution with required sample time. Once sufficient signal resolution is achieved, further reduction of wheel speed would only increase measurement time due to extended thermal transients.

Improved Tilt and Angle Measurements

Even with improved gyro technology, a sub-arc second system level accuracy is not realistic without consideration of refined tilt motion detection and improved azimuth transfer. Once again, each of these areas is substantially accuracy-limited by the mechanical motion of the ALS during gyrocompassing, since changes in the orientation of the gyro during the four-position sample sequence cause tilt- and thermal transients. These transients differentially decay during each sample interval, resulting in unpredictable errors in the ALS azimuth estimate. Further, differential movement of the two ALS mirrors during a sequence and between sequences also degrades accuracy.

By using wheel speed modulation, and thereby eliminating the need for gyro-compassing, each of these error sources will automatically be greatly reduced. Yet additional improvements are still required. Thus, the performance characteristics of the tiltmeters, autocollimator and inductosyn table have been and will continue to be critically examined. Instrument sample rates, frequency response characteristics and data processing will be matched to critical gyro parameters and new state-of-the-art technology employed where warranted.

Improved Automation

Currently the AAMS is controlled by a dedicated microprocessor which interfaces with each major component. The major components (ALS units, autocollimator, tiltmeters, etc.) are controlled by their own unique discrete logic. In addition to controlling the experiment this hardware acquires all experimental data, digitally filters analog data, and records all data on magnetic tape. The system is designed to be self contained and run unattended.

A second microprocessor is used to provide a quick field analysis of the experimental data. This microprocessor can provide real time multi-channel data plots and regression analyses of short data segments and other operator-discretionary analyses. Complete data reduction and analyses are done through post-processing on AFGL's general purpose computer.

However, the present AAMS is limited by the extensive amount of discrete logic and minimal field data processing capability. To relieve these problems, a new distributed data processing system is now under development (see Figure 6). It consists of three LSI-11 and one LSI-11/23 microprocessors configured in a hierarchical network.

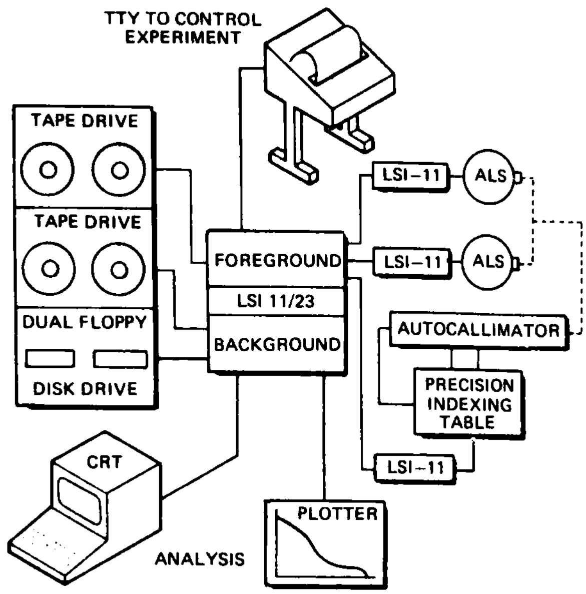

Figure 6. AAMS Distributed Data Processing System

In this new configuration, each ALS and its associated sensors will be controlled by a dedicated microprocessor. A third microprocessor will be used to control the precision indexing table, autocollimator, and the remaining system sensors. These three microprocessors will then transmit their pre-processed data to an LSI-11/23 which would record it on tape.

The LSI-11/23 uses a foreground/background operating system. While the data acquisition and recording program is running in the foreground, one of several data processing programs could also be run in the background to analyze and plot experimental data. These data could be processed real-time as they are being recorded, or after data acquisition through use of a second tape drive.

This new distributed configuration will provide several advantages. Discrete logic will be replaced by software; local data processing capability will be enhanced; and self-control will be incorporated through built-in data checks.

The replacement of discrete logic with software will greatly improve experimental flexibility. Data sample rates, filtering schemes, and timing and control functions can be quickly changed through a remote keyboard rather than hardwiring at the test site.

The addition of a background data processing capability will increase processing capacity and allow field processing prior to experiment teardown. This capability provides confirmation of data integrity before the system is disassembled for transport.

Finally, the system will monitor its own status and periodically print values for variable parameters. This will provide greater security against failure and ensure data integrity.

IV. SUMMARY

Throughout the next decade the Guidance and Control Community will be striving to meet or exceed stringent accuracy goals for major new weapons systems. One of the single most important contributions to satisfaction of these goals must be the achievement of sub-arc second azimuth accuracy at the instrument test level. The Automated Azimuth Measuring System presently addresses this need by providing a portable azimuth reference, but new accuracy demands are quickly surpassing its capability.

The planned improvements will provide for a state-of-the-art, portable azimuth measuring system which should satisfy the needs of the DoD for the next decade. This system would be capable of measuring small environmental motions which inhibit test and evaluation of new generation inertial instrumentation, as well as verification of performance of present inertial measurement units at the instrument, sub-system or system level.

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